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Title:	Dominating the Electromagnetic Spectrum with Spatio-Temporal Modulated Metasurfaces
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Dominating the Electromagnetic Spectrum with Spatio-Temporal Modulated Metasurfaces

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Introduction

The effective control and manipulation of electromagnetic waves play a critical role in attaining enhanced performance of electromagnetic systems. Spatio-temporal modulated metasurfaces – dynamic two-dimensional arrays of sub-wavelength resonators with arbitrary phase reconfigurability – have the potential to enable full dominance of the electromagnetic spectrum and revolutionize remote sensing and imaging. Based on this concept, we will develop and prototype microwave steerable and deployable flat antennas with reduced size, weight, and power requirements for SmallSats applications. Furthermore, in order to achieve independent control over the transmission and reception modes of our flat antennas, we will demonstrate spatio-temporal modulated metasurfaces that break Lorentz reciprocity.

Project Goals

Modern communication, sensing, and surveillance systems rely heavily on the utilization of the electromagnetic spectrum for collecting information, controlling instruments, and making decisions. SmallSats, an emerging geo-spatial capability for remote sensing and imaging, are a key component of LANL mission space in Science of Signatures. However, they are intrinsically constrained in SWaP (size, weight, and power), and are in dire need of revolutionary design paradigms to enable dramatically increased performance. We propose to develop transformational electromagnetic systems for space applications by integrating spatio-temporal modulated metasurfaces (STMMs), which are two-dimensional arrays of sub-wavelength metallic resonators with dynamically reconfigurable amplitude and phase profiles. Such a technology will be a game-changer for SmallSat-scale instrument miniaturization via the dynamic on-demand control capabilities. In this proposal, we will demonstrate how STMMs enable unprecedented dominance of the microwave spectrum. We will develop STMM antennas capable of active wavefront correction and wide-angle beam steering through creating electrically programmable metasurfaces (see Fig. 1). We will then prototype foldable and deployable active metasurface antennas with high gain and broad bandwidth for communications and remote sensing in SmallSat platforms. Once achieved, this spatio-temporal control offers a great opportunity to investigate the emergent key science concept of electromagnetic Lorentz non-reciprocity, thereby allowing for independent manipulation of reception and transmission in STMM antennas. The STMM concept can be possibly translated into other frequencies, including the technologically relevant terahertz and mid-infrared wavelength regimes, impacting a variety of SoS applications across a broad electromagnetic spectrum.

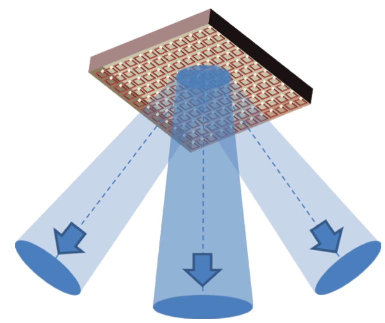


Fig. 1. Concept of a spatio-temporal modulated metasurface. The reconfigurable phase profile of the ultrathin flat metasurface enables continuous beam steering.

Background and Statement of Problem

Radio-frequency communications in SmallSat platforms require dynamically steerable antennas to overcome platform stability while maintaining the data link between moving objects. In addition, a larger-area antenna enables a commensurate reduction in transmitter power, but this is only feasible in a small spacecraft if the antenna is deployable, as well as steerable. Present-day approaches to these problems involve mechanically movable components that suffer from speed and reliability issues, and phased array technology that requires complex control systems and consumes excessive power [1, 2]. Further critical considerations for SmallSat antennas include high gain, broad operational bandwidth, and low cost. Parabolic dish antennas have been the most commonly used high gain antennas for maintaining communication links between large/medium-scale satellites and ground stations, but they are not viable options for small satellites. Conventionally, these employ dipole or helix antennas that are easily deployable but suffer from poor directionality and limited gain [3, 4]. Many approaches have been studied to increase the performance of antennas with reduced SWaP, including arrays of constrained patch antennas [5, 6] (which have low efficiency and bandwidth), and Fresnel zoned plate antennas (which suffer from zone edge blockage) [7, 8]. In regards to the antennas developed by the LANL superluminal project, they are bulky and require high current, thereby are unsuitable for SmallSat applications.

Recent advances in metasurfaces [9, 10] provide an excellent opportunity to address the aforementioned issues. These two-dimensional equivalent of metamaterials consist of planar arrays of subwavelength resonators, and can impart abrupt phase changes for light propagating through them, thereby enabling unprecedented capabilities for manipulation of electromagnetic waves. Judiciously designed metasurfaces allow independent control of the resonators' amplitude and phase response through engineering the subwavelength structure, and can create an arbitrary phase-gradient along the metasurface interface enabling arbitrary wavefront control, e.g., anomalous refraction and polarization conversion [11, 12] (see Fig. 2). Being ultrathin and light-weight, and possibly flexible and foldable, metasurfaces are ideally suitable for novel microwave antenna applications in SmallSats. Single-layer plasmonic metasurface-based flat lenses have been demonstrated at optical, terahertz, and microwave frequencies [13-17]. However, their focusing efficiencies are typically below 10% due to the weak interaction strength arising from their ultrathin nature. Although dielectric metasurfaces can address the efficiency issue in the optical regime [18-20], the resonator size and weight become too large to be suitable for microwave applications. In contrast, our recently developed innovative few-layer metasurfaces concept has significant advantages over single-layer metasurfaces, including dramatically enhanced efficiencies close to 100% [21, 22] and novel functionalities beyond those achievable by the individual metasurface layers [12, 23]. However, these structures are usually passive (i.e., time-independent) and non-reconfigurable. Active single- and few-layer metasurfaces, pioneered by LANL [24-27], have also been demonstrated through functional materials integration, and thermal, electrical, magnetic and optical stimuli. Although they have achieved certain degree of tunability (e.g., frequency tuning and phase shifting), they are still far from sufficient to realize fully reconfigurable functionalities.

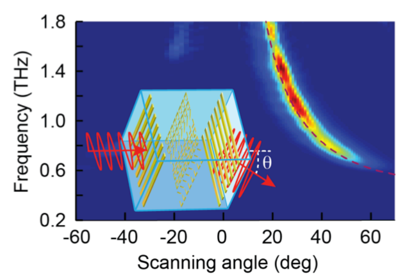


Fig. 2. LANL demonstration of anomalous refraction with a few-layer passive metasurface at THz frequencies [12]. The complex unit cell of the structure is shown, consisting of resonators of various shape, two crossed gratings, and dielectric spacer in-between. The color maps the experimental transmission under normal incidence as a function of frequency and scanning angle.

One basic electromagnetic principle that governs all above electromagnetic phenomena in metasurfaces is Lorentz reciprocity [28, 29]. In microwave systems, this implies that a good transmitter is also a good receiver, prone to detecting echoes or impairing external signals in highly dense electromagnetic environments, ultimately producing bleaching of the detection system. Lorentz reciprocity holds for systems that have symmetric permittivity/permeability tensors, are linear, and time-independent, and results in symmetric scattering processes. Breaking reciprocity will enable groundbreaking electromagnetic functionalities, e.g. different transmit and receive modes for STMM-based antennas. Various approaches have been proposed in the literature to break Lorentz reciprocity, including the use of magneto-optical effects [30] (requiring bulky magnets), nonlinear media [31] (but are power dependent), and spatio-temporal modulation [32]. There is only a single far-field experimental demonstration of this concept realized in a spatio-temporal modulated microwave slot-antenna with about 15 dB difference between receive and transmit patterns [33]. However, the used quasi-1D geometry does not allow breaking Lorentz reciprocity in arbitrary directions.

Preliminary studies

During the past years, we have developed few-layer ultrathin metasurfaces for novel electromagnetic functionalities, including the demonstration of broadband linear polarization conversion and complete control of phase [12]. Recently, we have demonstrated metasurface-based ultrathin flat lenses operating at terahertz [21] and microwave [22] frequencies. Figure 3 shows a series of concentric subwavelength metallic split-ring resonators (SRRs), sandwiched between two cross-polarized metallic gratings, designed with a radially symmetric parabolic phase distribution covering relative phase differences ranging from 0 to 2.5π radians. The fabricated lens has a measured gain of 17 dBi at 9.0 GHz, bandwidth extending from 7.0 to 10.0 GHz, and 3dB directionality less than 4.5º, confirming high-quality beam collimation. Such metasurface lens is lightweight, low-cost, and can be easily deployable.

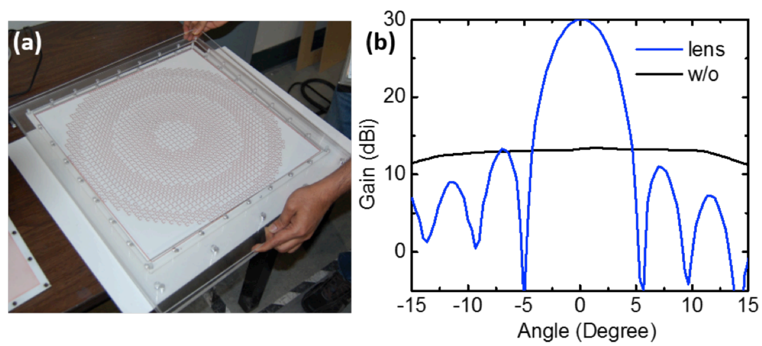


Fig. 3. LANL microwave metasurface flat lens. (a) Picture of the 18×18 in^2 fabricated structure. (b) Measured gain as a function of angle for a horn antenna (black) and metasurface antenna (blue).

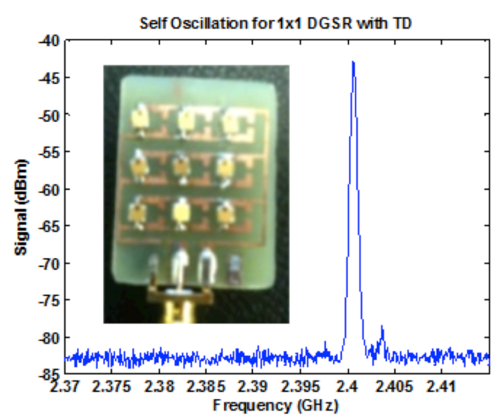


Fig. 4. Metasurface resonators with active gain elements: microwave signal generated from resonators integrated with tunnel diodes. The inset shows a metasurface consisting of 3×3 resonators array.

We have also carried out extensive experimental work in active metasurfaces, realizing active response via functional material integration. Recently we have demonstrated metasurface resonators operating at microwave frequencies integrated with tunnel diodes as gain elements, which generates microwave signals (Fig. 4) when driven with a DC voltage bias.

Proposed Innovation and Significance

Based on LANL's recent successes in fundamental research on metamaterials [24, 34-36], as well as emergent concepts in electromagnetics [31-33], we propose to take the next step and use metasurfaces for SoS forward deployment applications. *The key innovation of this proposal is to empower metasurfaces with spatio-temporal control to enable groundbreaking active and tunable response for SmallSats sensing, imaging, and communications, while simultaneously reducing their SWaP requirements*. Besides the spatial phase gradients inherent to the subwavelength resonator arrays, which are static and fixed by geometry, additional spatial phase modulation can be incorporated into the structure, for example via programmable varactor diodes integrated into the metasurfaces. The inclusion of temporal modulation can expand even further their electromagnetic functionalities. The marriage of spatio-temporal modulation with few-layer metasurface antennas has the potential to overcome the limitations of existing active metamaterials and herald a quantum leap in small satellite communication technologies.

Technical impact

The main technical significance of our proposed spatio-temporal modulated metasurfaces is their potential to address key science and technology issues encountered in the small-scale satellite platforms for communications, sensing and imaging. This potential can be realized using our innovative few-layer metasurfaces empowered with spatial and temporal control, accomplishing fully reprogrammable phase profiles for data link preservation, active wavefront correction, dynamical beam forming, and continuous beam steering. Our spatio-temporal modulated metasurfaces also address the SWaP requirements of SmallSats since they are ultra-thin, lightweight, and low power, in addition to being broadband, flexible, foldable, and deployable. Furthermore, independent control of the transmission and reception profiles of metasurface antennas can be potentially realized by employing appropriate spatio-temporal modulation that breaks Lorentz reciprocity. The development of a space- and time-gradient few-layer metasurface platform, together with its implementation in high-impact SmallSat applications, makes our work unique and will maintain LANL's leadership in this field of research.

Mission impact

This project underpins the LANL mission in Science supporting National Security, and advances sensing capabilities for space situational awareness in Global Security. Our proposed work addresses the FY18 Science of Signatures SIP core themes of Revolutionize Measurements and Forward Deployment, and aligns with its Sensing of Space and Adaptive Sensing Systems for National Security priorities. It leverages the fabrication and characterization capabilities in CINT. This project builds on LANL's extensive fundamental research in metamaterials and metasurfaces supporting mission relevant applications. This effort will explore a collaborative process where the developing science will be directly applied to ISR's small-satellite programs.

R&D Methods and Anticipated Results

Our R&D approach will capitalize on LANL's recent successes in fundamental metasurface research and the strong LANL SmallSat program. We will perform a systematic investigation of spatio-temporal modulated metasurfaces and their application in small satellite antennas following an approach that integrates and synergistically couples theory, design, fabrication, characterization, and prototyping. This project consists of two major tasks as described in detail below.

Task 1: Reprogrammable microwave metasurface antennas for active beam steering and wavefront correction

In order to achieve a reconfigurable metasurface device, it is necessary to address each individual metasurface resonator so that an independent control, e.g., voltage bias, can be applied to tune its resonant response including amplitude, phase, and polarization states. This requires connecting metal wires between the device and voltage sources. Although a transmissive metasurface might be advantageous in system design and deployment for certain applications, the metal wires unavoidably interfere with its resonant response, making the design of such a device too complicated if not impossible. In contrast, in a metasurface operating in reflection, the metallic wires can reach the resonators through via (vertical interconnect access) connections, but are otherwise hidden behind a metal ground plane so they will not interfere with the incident waves. The via connections become part of the metasurface structure and will be considered during the design stage. Reflective metasurfaces dramatically reduce the complexity in accomplishing active functionalities as compared to the case of transmissive metasurfaces, thereby providing the device configuration of choice for the demonstration of spatio-temporal modulated metasurfaces.

In our first subtask, we will demonstrate a static flat metasurface reflector that can focus plane waves radiated from a source far away or convert diverging waves radiated from a source located at its focal point to a collimated beam, essentially the same function of a dish reflector with a parabolic curvature. Wavefront engineering can be accomplished through the insertion of a desirable phase profile, which requires the phase of individual pixels to vary and cover a full 2π range. The proposed flat metasurface reflector consists of an array of subwavelength anisotropic resonators of different geometries backed with a metal ground plane, as shown in Fig. 5(a). The individual resonators scatter the incident linearly polarized beam to its cross-polarization with high efficiency and, more importantly, acquire a scattering phase-jump determined by the resonator's geometry [12] (see Fig. 5(b)). We will design, fabricate, and characterize such a static flat metasurface reflector operating at frequencies within the 10-20 GHz range.

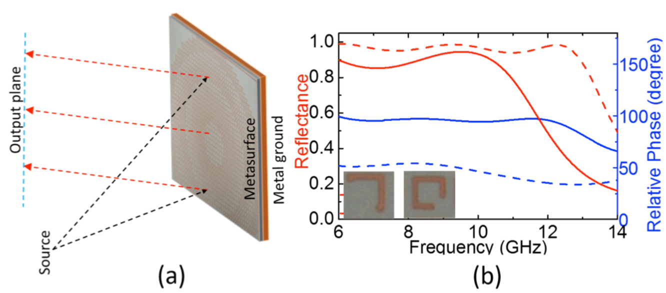


Fig. 5. Beam collimation using a metasurface with spatially modulated geometry. (a) Schematic of the metasurface structure with a parabolic phase profile achieved by arranging different resonators in a way similar to Fig. 3. (b) Simulated reflectance (red curves) and phase (blue curves) for two representative resonators shown in the inset, solid curves for the structure at left and dashed curves for the right.

Our second subtask is to demonstrate reprogrammable flat metasurface reflectors to enable active beam steering and wavefront correction. A candidate resonant structure suitable for this purpose is shown in Fig. 6(a), which possesses a phase dispersion varying from $+\pi$ to $-\pi$ while it remains highly reflective within the frequency range of interest, as shown in Fig. 6(c) and (d). Its resonance frequency can be actively tuned through the integrated varactor diode, which is a type of semiconductor device whose capacitance can be varied over a wide range of values upon applying a voltage bias. The resulting shift of the phase dispersion provides the required phase coverage at a specific frequency, allowing for creating an arbitrary phase profile. We will design, fabricate, and characterize such an active flat reflective metasurface schematically shown in Fig. 6(b), and concurrently develop the control circuit to supply the required voltage biases. These voltages will be applied to the identical varactor diode integrated resonators to obtain a parabolic phase profile for collimating the incident beam from a source. Furthermore, by changing the voltage biases, we will be able to rapidly (~millisecond or faster) reprogram the phase profile, thereby actively steering the beam to a desirable direction over a wide range of angles (~90°). From our preliminary simulations, we expect this metasurface device to have more than 90% reflectivity and a gain higher than 20 dB for a ~50×50 cm^2 active device area.

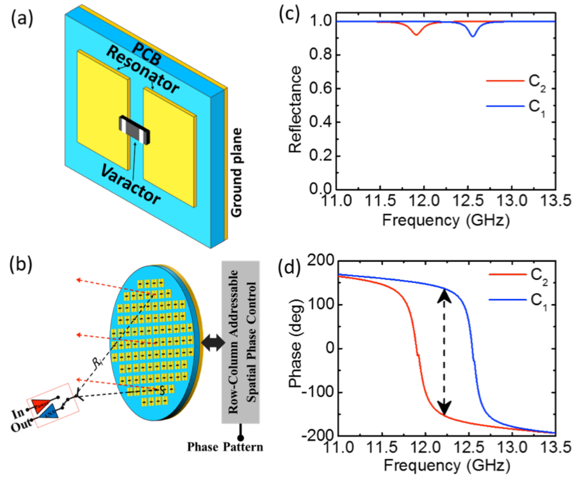


Fig. 6. Active beam steering using spatio-temporal modulated metasurfaces. (a) Schematic of a resonator operating at 12 GHz with integrated varactor diode. Unit cell dimensions: 8 × 8 mm^2. Not shown are the via connections to supply the voltage bias. (b) Schematic of the flat metasurface reflector where individual resonators are biased with different voltages, creating an arbitrary phase profile for active beam collimation and steering. Simulated (c) reflectance and (d) phase for the resonant structure in (a) applied with different voltages represented by the capacitance values C_1 = 2 pF and C_2 = 1 pF. The vertical arrow indicates the range of phase that can be covered at a specific frequency.

Our third subtask is to design and prototype a stowable and deployable metasurface antenna for SmallSat platforms. The key considerations for SmallSat antennas are their ability to stow in a small form factor and reliable deployment. We will employ a simple mechanical hinge approach which has been demonstrated to be a low-risk method suitable for space applications. We will design and prototype such a mechanical hinge system, and study the effects of the deployment on the metasurface antenna performance. A static metasurface developed in our first subtask will be segmented into small pieces and will be attached to a collapsible frame accordingly so that after the deployment it can retain its original shape, as schematically shown in Fig. 7. The hinge design will incorporate a shape memory alloy (e.g., nickel-titanium alloy), which will provide the necessary deployment torque in the antenna frame. The performance of the deployed antenna (gain, beam collimation, directivity and bandwidth) will be measured and compared directly with the values obtained from our first subtask. We will then translate the developed deployment method to the reprogrammable metasurface antennas for active beam steering in a SmallSat platform.

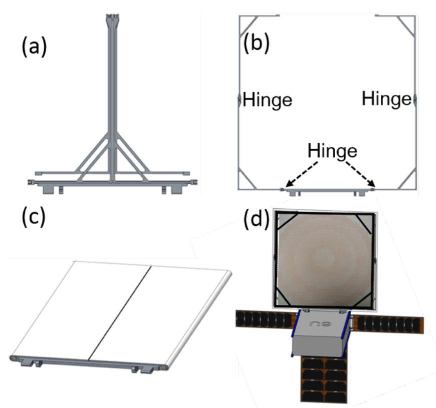


Fig. 7. Conceptual design of a stowable and deployable method for metasurface antennas. (a) Schematic of a stowable folded frame that can be unfolded by using two pairs of hinges (b). A metasurface reflector attached to the folded frame (c) and a schematic of a CubeSat with deployed metasurface antenna and solar panels (d).

Task 2: Harmonic spatio-temporal modulated metasurfaces

Spatio-temporal modulated metasurfaces may exhibit novel counter-intuitive properties that will further extend the functionality achievable from metasurfaces and expand the fundamental understanding of wave-matter interactions. *In the first subtask, we will theoretically investigate harmonic spatio-temporal modulated metasurfaces as an alternative approach to wavefront control.* In contrast to the active metasurface shown in Fig. 6 by applying static but reprogrammable voltage profiles, here we consider harmonic spatio-temporal modulations. As an example, Figure 8 shows dynamical microwave focusing attained through a flat metasurface whose electrical permittivity is modulated as $\epsilon(x,t) = \epsilon_0 + \delta\cos[\Omega t + \phi(x)]$, where ϵ_0, δ, and Ω are the static permittivity, modulation amplitude, and modulation frequency, respectively. On-demand focusing of the normally incident electromagnetic field can be achieved in an arbitrary direction by properly designing the phase profile of the modulation to satisfy $\phi(x) = k\sqrt{(x - x_f)^2 + y_f^2}$, where x_f and y_f are the targeted focus coordinates, and k is a constant with values comparable with the incident wavenumber. These metasurfaces will be modeled using Floquet-Bloch theory to expand the electromagnetic field as a superposition of spatial and temporal modes [37, 38]. We will analyze the resulting infinite set of coupled equations for momenta and frequency harmonics using various approximation methods, including perturbative expansions in small modulation amplitudes, slow modulation frequencies, and effective medium approaches. We will use these analytical tools to design the required modulation profiles suitable for a given application (e.g., active beam steering, focusing, wavefront shaping), and carry out numerical simulations to test the predicted modulation profiles.

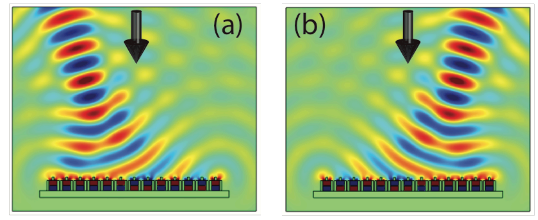


Fig. 8. Numerical study of focusing using a simple spatio-temporal modulated metasurface. The normally incident plane wave at ω = 6.8 GHz is mixed with the STMM modulation at Ω = 3.1 GHz, resulting in 9.9 GHz reflection that can be focused to the left (a) or right (b) depending on the modulation profile (see text). Parameters are: δ/ϵ_0=0.1, x_f=±5cm, and y_f=12cm. The lateral size of the STMM is 17cm.

In the second subtask, we will theoretically investigate Lorentz non-reciprocity to attain independent control of the transmission and reception modes of our STMM antennas. In Fig. 9(a) we explain the concept of Lorentz non-reciprocity for light reflection on an STMM. Consider an electromagnetic wave at frequency ω impinging on the metasurface (red arrow). In the absence of any kind of modulation, there will be specular reflection following the usual Snell's law (light red arrow). With spatial modulation only, the surface imparts a tangential momentum Δk_x to the wave, which then reflects non-specularly as in a phase gradient metasurface shown in Fig. 5(a). When harmonic temporal modulation at frequency Ω is added, the frequency of the reflected wave is also shifted (e.g., $\omega + \Omega$ shown by the green solid arrow). If the structure were reciprocal, when the wave is sent back towards the metasurface (dashed green arrow) it should reflect into the same direction and frequency as the original input beam (red arrow). However, because of spatio-temporal modulation, the output beam reflects with a different angle (dashed red arrow). One possible way to understand the non-reciprocal reflections shown in Fig. 9(a) is based on the dispersion relation of the metasurface resonant modes (see Fig. 9(b)) [39]. In the absence of spatio-temporal modulation, the metasurface dispersion (solid curve) is symmetric with respect to $k_x = 0$, where forward ($k_x > 0$) and backward ($k_x < 0$) incident waves equally excite the resonators (blue dots). Spatio-temporal modulation breaks time-reversal ($t \rightarrow -t$) and

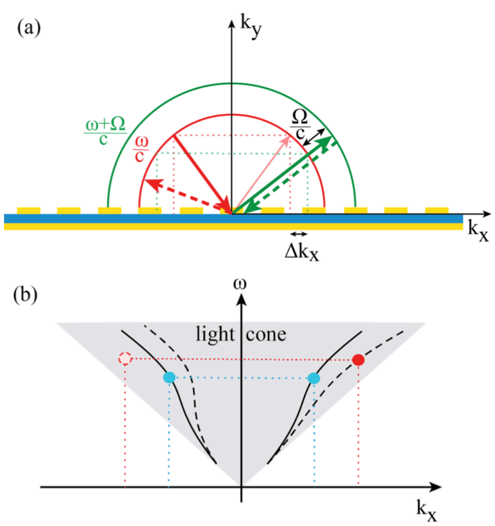


Fig. 9. (a) Schematic showing non-reciprocity in reflection for an STMM. (b) Example of dispersion relation of resonant modes of an unmodulated (solid curve) and modulated (dashed curve) metasurface. See text for details.

spatial-inversion ($\boldsymbol{r} \to -\boldsymbol{r}$) symmetries, resulting in asymmetric dispersion (dashed curve). This allows, for instance, the metasurface resonant response to be excited only through forward modes (red dot), thereby breaking reciprocity.

We will make use of state-of-the-art analytical and numerical tools to design a non-reciprocal STMM with maximum violation of Lorentz reciprocity in the microwave regime. We will employ the Floquet-Bloch theory to determine the dispersion curves of the resonant modes, and then identify the appropriate conditions that lead to asymmetric dispersion relations $\omega(\boldsymbol{k}) \neq \omega(-\boldsymbol{k})$. In the case of a weak spatio-temporal modulation, analytical perturbative approaches based on coupled-mode theory will be utilized to characterize the far-field scattering profile and compute the metasurface's unbalanced reflectivities. In the regime of strong modulation we will numerically solve the full set of Floquet-Bloch coupled equations for momenta and frequency harmonics using in-house rigorous coupled wave approach (RCWA), time-dependent multipole expansions, as well as finite element methods (e.g., COMSOL).

In the third subtask, we will experimentally validate non-reciprocal transmission and reception in STMMs. A schematic of a possible metasurface design, employing split-ring resonators integrated with varactor diodes, is shown in Fig. 10. We will first measure the dispersion relation when the structure is unmodulated (solid curve in Fig. 9(b)), by scanning the specular reflection as a function of incidence angle and frequency. Based on the theoretical predictions for maximal asymmetric dispersion in the modulated metasurface (including modulation frequency Ω, amplitude ΔV, and spatial profile $\phi(x)$), the new dispersion relation will be similarly obtained (dashed curve in Fig. 9(b)). Note that in this case we will need to scan the reflection frequency (near $\omega \pm \Omega$) and angle as the reflection is not necessarily specular. Such measurements also provide information to verify the non-reciprocity in reflection: $R_{\theta_i \to \theta_r}(\omega \to \omega \pm \Omega) \neq R_{\theta_r \to \theta_i}(\omega \pm \Omega \to \omega)$, schematically shown in Fig. 10.

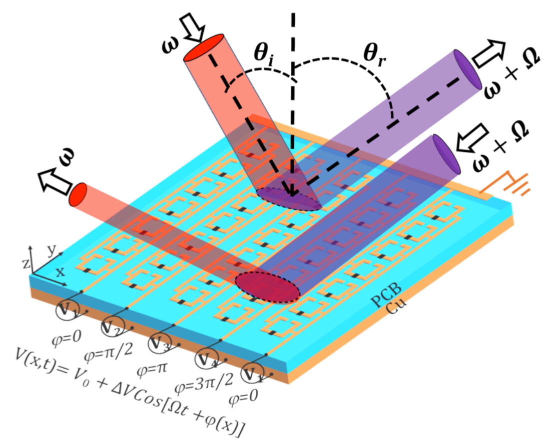


Fig. 10. Schematic of a spatio-temporal modulated metasurface for experimental demonstration of nonreciprocal reflection.

Methods

Full-wave numerical simulations will be carried out for metasurface structure designs using licensed commercial packages CST Microwave Studio and COMSOL Multiphysics, which have been extensively used in our metamaterials and metasurface research. We will define a unit cell to obtain resonant response (reflection amplitude and phase dispersion) by implementing actual materials properties and suitable boundary conditions (e.g., periodic boundary condition) without varactor diodes. Then we will integrate varactor diodes (e.g., Skyworks SMV1405), which will be simulated as lumped circuit elements within the resonators using SPICE models. We will sweep the geometric parameters to achieve the desirable resonant response.

The designed metasurface structures will be fabricated using our in-house PCB milling machine (Quick Circuit Prototyping Systems from T-Tech) and through foundry sub-contractor (BiRa Systems Inc.). Varactor diodes will be mounted into metasurfaces using facilities available in ISR or through commercial vendors. We will use a row-column addressing scheme, an architecture commonly used in digital random-access-memory (RAM) circuits, to supply the voltage bias to the varactor diodes for phase control, and the reprogramming will be conducted using National Instruments (NI) DAQ modules and LabView. Alternatively, we can use commercially available field programmable gate arrays (FPGAs), which independently control individual varactor diodes in parallel. In the case of realizing harmonic spatio-temporal modulation to achieve non-reciprocal metasurfaces, the resonators will be connected into rows, as shown in Fig. 10, using a pair of appropriately designed interdigitated strip lines as input terminals. A wideband bias-T (e.g., TCBT 14+ from Minicircuits) can be used to combine a modulation RF signal with the DC voltage bias at each input terminal. The modulation signal of frequency Ω and amplitude ΔV will be generated by a tunable RF source and transmitted through a multichannel phase shifter to attain the required phase $\phi(x)$.

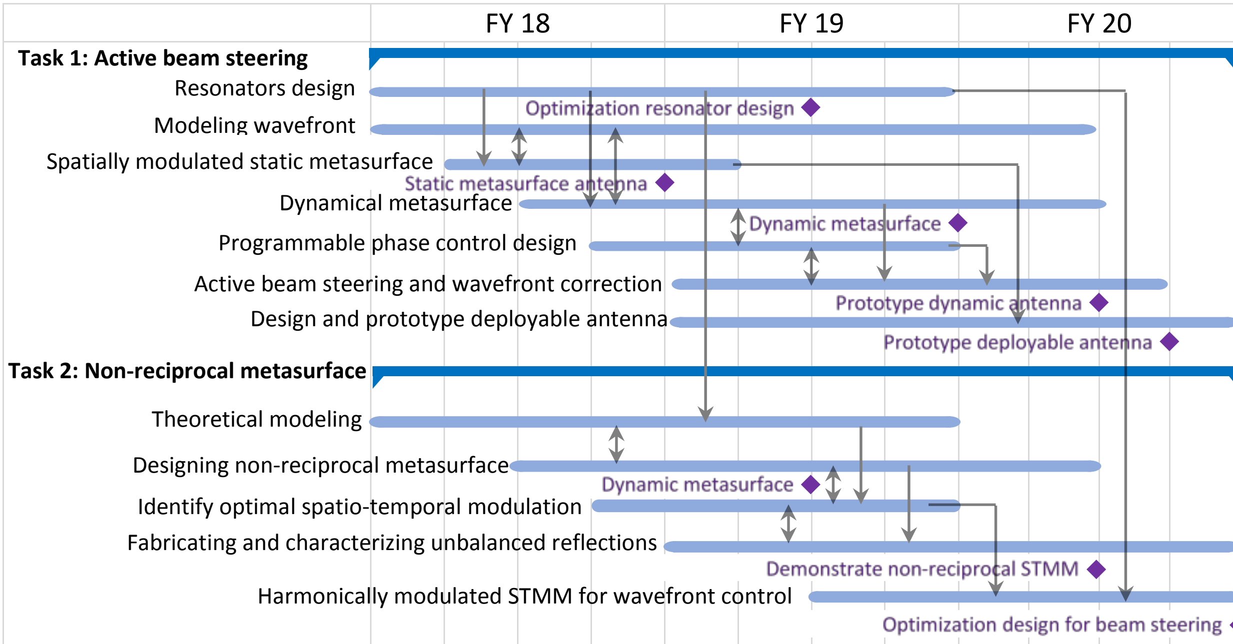
The characterization of the STMMs will be performed using our in-house anechoic chamber equipped with multiple sources and receivers (patch antennas and horn antennas), a vector network analyzer (VNA), a spectrum analyzer, and a broadband microwave analyzer, covering the desirable frequency range. To obtain the phase-voltage relation, we will use a metasurface with identical resonators and measure the reflection amplitude and phase as a function of the voltage that is uniformly applied to all varactor diodes. The obtained results will be used to create the voltage profile for active beam collimation and steering, as well as wavefront correction. In such measurements, we will use an appropriate microwave source at off-axis incidence (shown in Fig. 6), and measure the reflected beam profile as a function of tilt and azimuthal angles under different voltage profiles. The spatio-temporal modulated metasurfaces will be characterized using a tunable microwave source and spectrum analyzer, which allows us to measure the angle-dependent reflectivity as a function of input and output frequencies.

Expected results

Upon successful completion of this project, we will deliver: a) A flat metasurface reflector for microwave beam focusing/collimation; b) Demonstration of reprogrammable and deployable metasurface antennas for active beam steering through integration of varactor diodes and a bias control system; c) Development of theoretical models and simulation capabilities to understand the non-reciprocal properties in spatio-temporally modulated metasurfaces; d) Experimental validation of non-reciprocity in spatio-temporal modulated metasurfaces. The metasurface-based prototype antennas operate at X-band (8 to 12 GHz), have an area of about 50×50 cm^2, reduce dramatically SWaP (weight 100s grams, stowage volume < 0.1 U, and power 100s mW), and significantly enhance the performance with gain >20 dB (~10× better than helix antennas [17]), bandwidths >30% (~5× better than reflect-/transmit-arrays), and beam steering angle ~90°.

Project plan

The close coupling of the basic science and application via cleared PI's will enable the development of promising classified follow-on applications. The PI and the ISR Co-PI, both holding Q-clearance, will pay careful attention to classification issues and build firewalls to clearly separate basic science done in unclassified settings from potentially classified applications. We will also identify and implement appropriate controls necessary to address security and export control issues.



Data management plan

Our team members have extensive experience in processing research results and backup data. Data and results will be first shared among team members as appropriate in our biweekly meetings, and will be used to update LANL program managers. External distribution of data will be through scientific publications and conference presentations after LANL internal classification process. Azad will manage the project, distribute data, and serve as the primary point of contact.

Transition plan

The proposed work should elicit numerous funding opportunities. The PI has been involved in discussions with Intelligence agencies regarding actively modulated metasurfaces and their possible SoS applications in SmallSats including communication, imaging, and surveillance. Potential customers also include DARPA (DSO & TTO offices), DOE (NA22), DTRA, SOCOM, and WFOs. During the course of the project, we will update LANL managers to identify and interact with external customers for further program development. In particular, we will closely work with Eric Dors (Program Director, GS-IET), Roger Petrin (GS-NA221), and Robert Shirey (Program Director, GS-DNC) by updating them about the project progress and new scientific discoveries. We will consult with David Pesiri (Feynman Center for Innovation) to ensure IP protection and possible commercialization of the technology.

Budget Request

We have formed an interdisciplinary research team (see Appendix) with the necessary expertise to successfully meet all the goals of this project. The requested budget is mainly to cover the labor cost for staff members (0.9 FTE in MPA, 0.65 FTE in T, 0.5 FTE in ISR, 0.25 FTE in AET) and postdocs. The M&S is for sample preparation through commercial vendors, simulation software licenses, microwave lab maintenance, minor equipment needs, conference travel, and publication fees.

Citations

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Appendix

The proposed research becomes possible because of recent breakthroughs made by our team members, particularly in the area of few layers metasurfaces and their applications in wavefront control. Combining with LANL's strong SmallSat program, our proposed work places LANL in a unique position to address enduring issues in reducing SWaP requirements of electromagnetic systems for SmallSat platforms. We have formed a team with demonstrated collaborative track record, and diverse but complementary expertise required for this multidisciplinary project. MPA will be in charge of design, fabrication, and characterization of spatio-temporal modulated metasurfaces. ISR will provide expertise in programmable metasurface phase controller, RF measurements and model based analysis, and requirements of deployable devices for SmallSat applications. T will provide the required theoretical expertise in modeling and simulations for spatio-temporal modulated non-reciprocal metasurfaces.

Abul Azad (PI) (MPA-CINT, 0.5 FTE) is an experimentalist in electromagnetic metamaterials, microwave engineering, and terahertz technology. He received his M. S. and Ph. D. in Electrical and Computer Engineering from Oklahoma State University in 2003 and 2006, respectively. From June 2006 to January 2007 he was working as a Postdoctoral Research Associate in the Department of Physics, Rensselaer Polytechnic Institute. He came to LANL in January 2007 as a Postdoctoral Research Associate and then was converted to a technical staff member in 2010. His research interests are in the area of few-layer metasurfaces and their applications, metasurface inspired microwave antennas, terahertz, and ultrafast optics. He was the PI on an LDRD-ER project on metamaterial based rectenna for microwave energy harvesting (10/2009-9/2012), Co-PI on an LDRD Mission Foundation, Co-PI on an LANL sponsored NMSBA project (01/2015-12/2017), PI on a Naval Surface Warfare Center sponsored SBIR project, and a lead scientist of an WFO project on metasurface based flat microwave lens (09/2015-08/2017). He authored more than 70 papers, including 1 science, 2 Nature Photonics, 2 Nature Communications, 3 PRLs, and one book chapter. These publications have received ~5500 citations. He has 1 issued patent and 1 patent disclosure. Abul will coordinate the overall efforts of the team and lead the experimental studies of the spatio-temporal modulated metasurfaces for SmallSat platforms.

<u>Selected publications relevant to this proposal:</u>

- Abul K. Azad, Anatoly V. Efimov, Shuprio Ghosh, John Singleton, Antoinette J. Taylor, and Hou-Tong Chen, "Ultra-thin metasurface microwave flat lens for broadband applications" *Applied Physics Letters*, accepted (2017).
- Abul. K Azad**,** W. JM Kort-Kamp, M. Sykora, N. Weisse-Bernstein, T. S Luk, A. J Taylor, D. A. R Dalvit, and H-T Chen, "Metasurface Broadband Solar Absorber" *Scientific Reports* **6**, 20347 (2016).
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- N. Grady, J. Heyes, D. Chowdhury, Y. Zeng, M. Reiten, A. K. Azad, A. Taylor, D. Dalvit, and H.-T. Chen, "Terahertz Metamaterials for Linear Polarization Conversion and Anomalous Refraction," *Science* **340**, 1304 (2013).
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Diego Dalvit (Co-PI) (T-4, 0.5 FTE) is a quantum optics theorist, with expertise in electromagnetism, metamaterials, Casimir physics, and quantum science. He received his Ph.D. in Physics from the University of Buenos Aires (Argentina) in 1998, came to Los Alamos in 1999 as a Director Funded Postdoctoral Fellow, and was converted to staff in 2002. He is a Fellow of the American Physical Society. He is presently the team leader of the Casimir/metamaterials team in T division and co-PI of an LDRD-DR project on mesophotonic materials for tailored light-matter interactions. Previously, he was the theory leader of two DARPA-funded projects on Casimir force control using metamaterials and plasmonics. He was a CNRS Visiting Professor at the Laboratoire Kastler Brossel, Paris, in 2010, and an Ecole Normale Superieure Visiting Professor in 2013. He coauthored a graduate textbook titled "Solved Problems in Statistical Physics" (Institute of Physics, 1999), co-edited another book titled "Casimir Physics" (Lecture Notes in Physics, Springer-Verlag, 2011), and recently published a Reviews of Modern Physics on the materials perspective of Casimir and van der Waals interactions. He authored 3 reviews, >95 publications, including 1 Science, 1 Nature Physics, 2 Nature Communications, and 12 PRLs. Diego will lead the theory efforts, will work on the modeling and simulation aspects of spatio-temporal modulated metasurfaces, and will closely interact with the experimentalists for experiment-theory cross-feedback and integration.

<u>Selected publications relevant to this proposal:</u>

- P. Rodriguez-Lopez, W. J. M. Kort-Kamp, D. A. R. Dalvit, and L. M. Woods, "Casimir force phase transitions in the graphene family", *Nat. Comm.* **8**, 14699 (2017).
- A. K. Azad, W. J. M. Kort-Kamp, M. Sykora, N. Weisse-Bernstein, T. S. Luk, A. J. Taylor, D. A. R. Dalvit, and H.-T. Chen, "*Metasurface broadband solar absorber*", Scientific Reports **6**, 20347 (2016).
- L. M. Woods, D. A. R. Dalvit, A. Tkatchenko, P. Rodriguez-Lopez, A. W. Rodriguez, and R. Podgornik, "Materials perspective on Casimir and van der Waals interactions", *Rev. Mod. Phys.* **88**, 045003 (2016).
- M. A. Wood, D. A. R. Dalvit, and D. S. Moore, "*Nonlinear electromagnetic interactions in energetic materials*", Phys. Rev. Applied **5**, 014004 (2016).
- W. J. M. Kort-Kamp, N. A. Sinitsyn, and D. A. R. Dalvit, "Quantized beam shifts in graphene", *Phys. Rev. B* **93**, 081410(R) (2016).

Bradly J. Cooke (Co-PI) (ISR-2, 0.2 FTE) received his PhD in 1989 from the University of Arizona with a background in both engineering and physics while specializing in electronics, systems, device (solid state) physics and electromagnetic fields. His research interests fall within the field of instrumentation physics and engineering with an emphasis on fundamental detection and noise processes limiting current nuclear, optical, and RF sensors – with the express purpose of developing and designing optimized next-generation detection systems. He is currently the ISR-2 Deputy Group Leader and a Project Leader with the NNSA/NA22 and Intelligence Program Office, who is tasked with the development of advanced sensor and instrumentation systems as applied to international security programs and proliferation detection technology. He has demonstrated experience in leading, developing, and delivering R&D projects within the DOE, DOD, national intelligence community, and reconnaissance community. Bradly will work on programmable meta-surface phase controller, RF measurements, and RF model based analysis.

<u>Relevant Papers and Patents:</u>

- Bradly J. Cooke, Amy Larson, Zachary K. Baker, Kimberly K. Katko, "Wideband Coherent Signal Processing Electromagnetic Pulse Detection and Discrimination Algorithms," Los Alamos National Laboratory, LA-CP –14-20189, August 7, 2014.
- Bradly J. Cooke, "A Relativistic Electrodynamics Framework for Far-Field Lightning Analysis and Modeling," Los Alamos National Laboratory, LA-UR 13-28238, January 29, 2014.
- Bradly J. Cooke, Amy Galbraith, William Junor, Kimberly K. Katko, Justin L. Tripp, Zachary K. Baker, and Thomas A. Carey, "Stationary-Phase Equalization Implementation and FPGA Resource Utilization," Los Alamos National Laboratory, LA-CP 13-00061, March 2013.
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- B. Cooke and D. Gunether, *Coherent Hybrid Electromagnetic Field Imaging*, U.S. Patent No. 7,417,744.
- B. Cooke and A. Galbraith, *Method and Apparatus for Coherent Electromagnetic Field Imaging Through Fourier Transform Heterodyne*, U.S. Patent No. 5,875,030.

Hou-Tong Chen (MPA-CINT, 0.4 FTE) is an experimental physicist in metamaterials and terahertz science and technology. He received his B.S. and M.S. from University of Science and Technology of China in 1997 and 2000, respectively, and a Ph.D. from Rensselaer Polytechnic Institute in 2004, all in Physics. He joined in Los Alamos in 2005 as a postdoctoral research associate, and was then converted to a technical staff member in 2008. Since 2010 he has been a CINT Scientist (supported by BES with 0.5 FTE). He has played the essential role in establishing the internationally recognized metamaterial program at LANL, pioneered the development of active THz metamaterials and devices, and the development and understanding of few-layer metasurfaces for perfect absorption, antireflection, polarization conversion, and flat optics. He holds 2 issued US patents and has published over 70 peer-reviewed articles in prestigious journals including *Science*, *Nature*, and *Physical Review Letters*, which have received over 7500 citations. He also delivered over 80 invited presentations at international conferences and accredited research institutions. He is a Topical Editor of *Optics Letters*, an elected Fellow of American Physical Society, and received LANL Fellows' Prize for Outstanding Research in 2015. Hou-Tong will be responsible for the design of metasurface structures for active beam steering and spatio-temporal modulation.

Selected publications relevant to this proposal:

- C.-C. Chang, D. Headland, D. Abbott, W. Withayachumnankul, and H.-T. Chen, "Demonstration of a highly efficient terahertz flat lens employing tri-layer metasurfaces," *Optics Letters* **42**, 1867–1870 (2017).
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- N. K. Grady, J. E. Heyes, D. Roy Chowdhury, Y. Zeng, M. T. Reiten, A. K. Azad, A. J. Taylor, D. A. R. Dalvit, and H.-T. Chen, "Terahertz metamaterials for linear polarization conversion and anomalous refraction," *Science* **340**, 1304 (2013).
- H.-T. Chen, "Interference theory of metamaterial perfect absorbers," *Optics Express* **20**, 7165 (2012).

- H.-T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, “Active terahertz metamaterial devices,” *Nature* **444**, 597 (2006).

Avadh Saxena (T-4, 0.15 FTE) is a condensed matter and materials theorist. He is Group Leader of the Condensed Matter and Complex Systems group (T-4) since 2009. Prior to coming to LANL in 1990 he held a joint postdoc position at Penn State and Cornell University. He is also an affiliate of the Center for Nonlinear Studies (CNLS). His main research interests include optical, electronic, vibrational, transport and magnetic properties of functional materials, device physics, soft condensed matter, phase transitions, nonlinear phenomena and non-Hermitian quantum mechanics. He holds adjunct professor positions at the University of Barcelona, Spain, Virginia Tech and the University of Arizona, Tucson. He is Scientific Advisor to National Institute for Materials Science (NIMS), Tsukuba, Japan. He has authored over 400 publications, edited four Springer books and many other specialized journal issues and co-organized over 40 international workshops/conferences. He is a frequently invited speaker at conferences and also as a colloquium speaker. He is a Laboratory Fellow and a Fellow of the American Physical Society (APS), and a member of the Sigma Xi Scientific Research Society and APS. Avadh will focus on the modeling of specific aspects of modulated metasurfaces.

<u>Selected publications relevant to this proposal:</u>

- B. Gardas, S. Deffner, and A. Saxena, “Non-Hermitian Quantum Thermodynamics”, *Scientific Reports* **6**, 23408 (2016).
- G.-W. Chern and A. Saxena, “PT-Symmetric Phase in Kagome-Based Photonic Lattices” *Opt. Lett.* **40**, 5806 (2015).
- S. Deffner and A. Saxena, “Jarzynski Equality in PT-Symmetric Quantum Mechanics” *Physical Review Letters* **114**, 150601 (2015).
- S. Gupta and A. Saxena, “A Topological Twist on Materials Science,” *MRS Bulletin* **39**, 265 (2014).
- A. del Campo, M.G. Boshier, and A. Saxena, “Bent Waveguides for Matter Waves: Supersymmetric Potentials and Reflectionless Geometries”, *Scientific Reports* **4**, 5274 (2014).
- J. Cuevas, P.G. Kevrekidis, and A. Saxena, “PT-Symmetric Dimer of Coupled Nonlinear Oscillators”, *Physical Review A* **88**, 032108 (2013).

Wilton Kort-Kamp (T-4, 1 FTE) is a theorist with expertise in photonics, nanostructured materials, radiative heat transfer, and classical/quantum electrodynamics. He received his Ph.D. in Physics from Universidade Federal do Rio de Janeiro (Brazil) in 2015, and came to Los Alamos in the same year as a Postdoctoral Research Associate. He received from the Brazilian Government the highest award conceded to a Ph.D. thesis defended in Brazil, namely the 2015 CAPES Award for Best Ph.D. Thesis in Physics and Astronomy. His work has also received several prizes for outstanding presentation at various conferences, including the School of Nonlinear Optics and Nanophotonics (ICTP-SAIFR, 2013), and the 3rd International Workshop on Fundamentals of Light-Matter Interactions (SPIE-UFPE, 2014). He has published 19 papers, including one Nature Communications, one PRL, one Scientific Reports, and several Physical Review papers. He has delivered 7 invited talks and 19 contributed talks. He is an active reviewer for various journals, including PRL, EPL, and Optics Letters. Wilton will work on the development of analytical and numerical tools to design and model spatio-temporal modulated reconfigurable metasurface antennas.

<u>Selected publications relevant to this proposal:</u>

- A. K. Azad, W. J. M. Kort-Kamp, M. Sykora, N. R. Weisse-Bernstein, T. S. Luk, A. J. Taylor, D. A. R. Dalvit, and H.-T. Chen, “Metasurface broadband solar absober”, *Scientific Reports* **6**, 20347 (2016).
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- W. J. M. Kort-Kamp, N. A. Sinitsyn, and D. A. R. Dalvit, “Quantized beam shifts in graphene”, *Phys. Rev. B* **93**, 081410(R) (2016).
- W. J. M. Kort-Kamp, F. S. S. Rosa, F. A. Pinheiro, and C. Farina, “Molding the flow of light with a magnetic field: plasmonic cloaking and directional scattering”, *J. Opt. Soc. Am. A* **31**, 1969 (2014).
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Nina Weisse-Bernstein (ISR-2, 0.3 FTE) is an engineer working on detection systems, with a variety of system design and engineering and device fabrication experience. She graduated with distinction from the University of New Mexico with an M.S. in Electrical Engineering in 2009. She has been staff at Los Alamos National Laboratory since 2005. Her research interests are in detection systems for ground based systems and satellites, and data analysis. Currently she is the deputy project leader and the principle engineer on a gamma detection subsystem on the Space and Atmospheric Burst Reporting System (SABRS-3), a nuclear detonation detection payload. Nina will work on active metasurface fabrications, RF characterizations, and developing deployable design concept.

Select Publications:

- Azad, A.K., Kort-Kamp, W.J.M., Sykora, M., **Weisse-Bernstein, N.R**., Luk, T.S., Taylor, A.J., Dalvit, D.A.R., Chen, H.-T. “Metasurface Broadband Solar Absorber”, *Scientific Reports*, 6, 20347 (2016).
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- Lin,S.-Z., Ayala-Valenzuela, O., McDonald, R.D., Bulaevskii, L.N., Holesinger, T., Ronning, F., **Weisse-Bernstein**, **N.R.,** Williamson, T.L., Mueller, A.H., Hoffbauer, M.A., Rabin, M.R., Graf, M.J. “Characterization of thin-film NbN superconductor for single-photon de-

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- Posani, K.T., Tripathi, V., Annamalai, S., **Weisse-Bernstein**, **N.R.,** Krishna, S., Perahia, O., Crisafulli, R., Painter, O.J. "Nanoscale Quantum Dot Infrared Sensors with Photonic Crystal Cavity", *Applied Physics Letters*, 88 **(15)**, 151104-1-3 (2006).
- Raghavan, S., Forman, D., Hill, P., **Weisse-Bernstein**, **N.R.**, von Winckel, G., Rotella, P., Kennerly, S.W., Little, J.W., Krishna, S. "Normal-incidence InAs, $In_{0.15}Ga_{0.85}As$ Quantum Dots-in-a-Well Detector Operating in the Long-Wave Infrared Atmospheric Window (8-12 microns)", *Journal of Applied Physics*, 96, 1036-1039 (2004).

Lee Holguin (AET-1, 0.25 FTE) is a mechanical engineer supporting the LANL space systems group (ISR) in mechanical design, mechanical analysis, and environmental testing. He received his B.S. and M.S. in Mechanical Engineering from New Mexico State University in 2010, and 2012, respectively. Joining first as a Post-Masters student in January 2014, he was converted to full-time staff in January 2015. Since his time as a student, he has supported the LANL space systems group with CAD/mechanical design, thermal and structural analysis, flight hardware environmental testing, and mechanical engineering requirements support. In 2016, Lee was awarded a LANL Small Team Distinguished performance award for work supporting the SENSER HRE project. Lee is currently the lead mechanical engineer on the SABRS and SENSER HRE projects; and is lead thermal engineer for the Prometheus CubeSat project. He has co-authored 4 conference publications relating to application of geometric mechanics for spacecraft rendezvous. Lee will work on the mechanical design and fabrication of the deployable metasurface antenna for the SmallSat platforms